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SIX MONTH INTERIM PROGRESS REPORT

Development of
Miniature Electromechanical Pressure Sensor Arrays (MEMPSA)
for High Resolution Thermospheric and Mesospheric
Neutral Wind Measurements

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I. Introduction and Background

This report documents progress made in the first six months on NASA contract NASW-5034. The goal of this project is to : (1) fabricate microelectromechanical systems (MEMS) based components as highly sensitive pressure transducers and (2) incorporate those transducers into a prototype instrument for the measurement of thermospheric and mesospheric neutral winds. The MEMS based components are tunnel displacement transducers (TDT's). TDT's are a new technology available because of simultaneous advances in microelectronics fabrication techniques, silicon micromechanics, and the use of quantum mechanical tunneling in robust, manufacturable devices.

The ability to implement TDT's in a highly sensitive instrument for pressure sensing in the upper atmosphere is dependent on fabrication and/or assembly of arrays of these transducers. Individual TDT's have been fabricated and demonstrated as robust, and thus the tunneling based technology is the primary candidate for this instrument development. In addition, robust capacitive sensors with lower sensitivity but more proven manufacturability have been demonstrated. Consideration of the capabilities and design tradeoffs for capacitive devices will be maintained throughout the course of this project.

This report has one major section and this brief introduction. The main section describes the work performed in pursuit of the first year milestones and the work in progress. This discussion is further divided into the three major components of the project : (a) transducer development, (b) electronics and hardware development for instrument implementation, and (c) software development for instrument implementation. The combination of work performed and work in progress is appropriate in that the project is in its early stages. In addition, some major program implementation changes have occurred. Although such changes can often be a diversion, we address the issues in the next section while sharing significant program gains due to the changes.

II. First Year Milestones and Work in Progress

As described in the proposal, milestones for the first year are : (1) Design and fabricate TDT's, (2) Design interface circuitry, (3) Design processing algorithms for real time analysis and (4) Build a breadboard circuit including a TDT or TDT array. These milestones can be achieved easily by maximizing effort employed in the design of the system. Milestones in future years will be impossible to achieve without extensive design effort in the first six to twelve months of the program. Therefore, a great deal of design effort is already expended, and much more is anticipated in the next twelve months. The project is initially divided into parallel efforts on the TDTs, hardware, and software. These three major tasks are not independent.

A. Design and fabrication of TDT components

Design

Design is the most important phase of the instrument development we are attempting. In order to assemble a reasonable prototype which can be transitioned to a manufacturing environment, we must "design for manufacture." This requires anticipation of system requirements and obviates component design based strictly on component performance optimization.

The innovation which allows for the detection of neutral winds in the upper, non-ionized atmosphere is a manufacturing and assembly technology. In order to make the pressure (P) measurements sufficiently rigid during a rocket flight, and sufficiently sensitive in a high

background pressure due to thrust velocity, **arrays** of TDT's are required. This program will be the first to demonstrate robust arrayed TDT's.

There are two somewhat different approaches which we must pursue while evaluating design trade-offs since they effect the instrument. Instrumentation is a system level problem, thus effects of a chosen approach on the system implementation are of primary concern. The two possible approaches at the device level are to integrate arrays of TDT's on a single chip, or to fabricate individual TDT's on a wafer, and package them individually for mounting in a multi-chip module. Figure 1 shows a side view schematic of a single TDT which can be fabricated and packaged individually. This schematic is similar to the devices from Jet Propulsion Laboratories (JPL) used as IR sensors. The JPL work has shown that individual TDT's can be fabricated and made robust for instrument applications. TDT's such as this can be mounted on a multichip module (MCM) for array implementation. Final packaging may require "encapsulation" which can be the thin layer of insulation material in Figure 1. We will therefore fabricate individual TDT's with this insulating layer. Figure 1 shows a side view schematic of multiple TDT's on a single wafer, which can then be diced to yield arranged TDT's integrated on a single chip. Such an integrated chip can them be packaged to complete the array implementation.

Figure 1

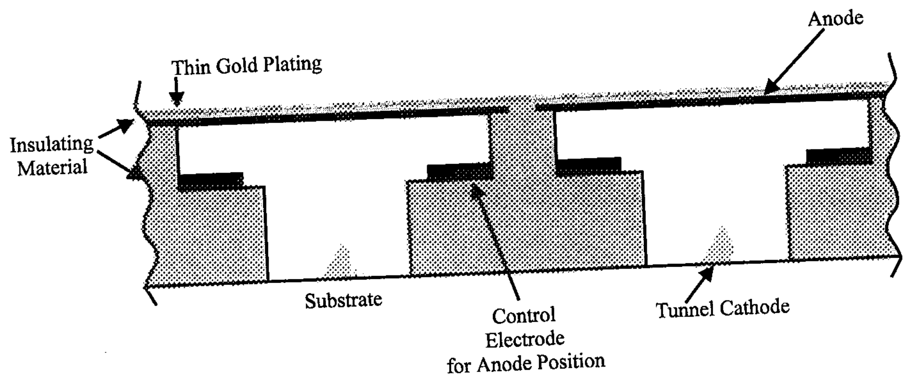
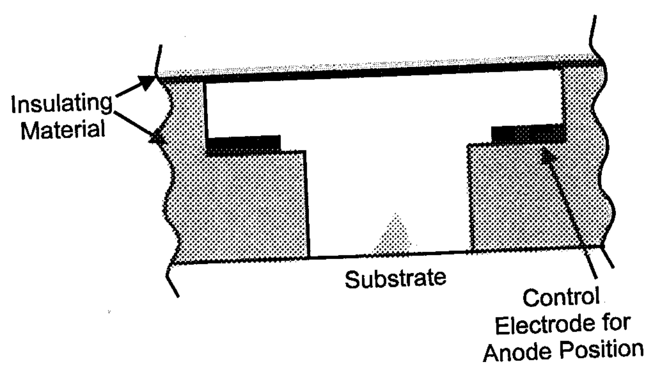


Figure 2



The difference in these approaches impacts the system in several ways. The decisions associated with the two approaches must be considered in the design stage, with particular emphasis on assembly and manufacturing. Since individual, robust TDT's are already achievable, we have come to the conclusion that our initial design matrix must include individual TDT's suitable for individual packaging, which includes the insulating layer discussed above. The individually packaged TDT's must then be suitable for an MCM or advanced printed circuit board (PCB) packaging scheme at the instrument level. A possible drawback to this approach is

the difficulty required to mount MCM's or PCB's on a flight instrument such that all component materials are protected from the ambient during flight. The effects of ambient are addressed by fabricating integrated TDT's with an additional Au layer, indicated in Figure 2. This layer will respond to issues regarding charging due to the ambient. We will initially fabricate arrays including the Au layer, leaving it off the single devices. This important design trade-off has been decided based on system level considerations.

We have considered the impact of chip-level integration of TDT's in the design phase. Of particular concern are the different P response ranges we must to detect and the device to device reproducibility. It is likely simpler to build individual TDT's with different response ranges in individual packages. In addition, the reproducibility of the device responses has been determined to be a lesser issue. Consider the triode structure, and realize that the only difference in response of individual devices fabricated in this manner will be small mechanical differences. These differences will be driven primarily by the multi-layer anode structure. If problems arise due to the Au layer, test structure can be evaluated using single devices. Most likely no new individual TDT's would be "fabbed." We would modify already tested devices by adding the Au layer later. Simple base line differences, within limit, can be overcome with different bias voltages between the control electrodes, and thus device to device reproducibility will be similar for individually packaged TDT's and integrated TDT arrays. The minor issue of cross talk between devices may limit the actual ability to control individual devices in the array but this can be overcome by changes in the physical distance between devices in the design, and will not affect spatial resolution of the instrument. A primary advantage to TDT's integrated at the chip level, is the possibility of including local drive circuitry on the same chip. This is quite realizable for some MEMS components already (including capacitively coupled accelerometer elements). We therefore have concluded that the next phase of design will include arrayed elements as shown in Figure 1. This figure and its details are the result of the initial design phase. For example, the inclusion of a conductive anode, insulating layer, and outer coating of gold is directly related to system requirements in flight as discussed.

MEMs Fabrication Facilities

Some changes in program execution have occurred since the award of this contract. First, and most important is that Dr. Gregory Earle has left SAIC to join the faculty of the University of Texas at Dallas (UTD) Physics Department. The benefits of the move far outweigh the drawbacks in terms of performance on the contract. Prof. Earle has joined a faculty involved for many years in space science research, and the interactions with these professionals can not be quantified with regards to the contract. In addition, we will now be involving students on this project directly, through subcontracts to UTD. This is an excellent opportunity for contribution of the academic world to the development of instrumentation, as well as an excellent opportunity for the education of students with regard to industrial approaches to solving problems and building hardware to study the space sciences. Another strong benefit is the addition of another fabrication facility available to the project. The best aspects of this are the fact that Prof. Earle is on site for supervising device fabrication and the facility has a significant portion of time to be dedicated to this work.

Clean room facilities suitable for fabrication of silicon-based MEMs pressure transducers have been identified. The cost for use of these resources at UT Dallas are currently being negotiated. Since fabrication & testing of these devices are specific objectives of the contract it is important to obtain access as soon as possible. The basis for establishing access to these facilities has been set up over the first six months of the contract.

Value-Added Academic Collaboration

Another significant change in the performance of this contract compared to the original proposal is the addition of the collaborative effort of Prof. Tom Kenney of the Mechanical Engineering Department at Stanford University. Prof. Kenney, formerly with JPL in Pasadena, has fabricated and characterized the performance of IR sensors based on TDT's. It was his initial work, along with Bill Kaiser and others at JPL, which showed that triode structures could be reliably fabricated, and resulting devices were robust. Prof. Kenney will save inestimable time in design and fabrication. For this reason we will begin with devices he has fabricated for characterization in our laboratory. Data from these devices will allow us to design the TDT's for this project at a much more advanced level. His collaboration has put us ahead by at least one if not two fabrication cycles in that the first devices we fabricate now will be that much more advanced. In addition, using photolithographic masks already available through Prof. Kenney, we have saved at least the first stage of "mistakes" which are inevitable in a program such as this one.

Value-Added Industrial Collaboration

A working relationship has been established with the Photonics and Micro-Machining Research and Development group at Texas Instruments, Inc. Engineers from TI have agreed to provide technical consulting services regarding MEMS fabrication techniques, device engineering, and system testing and evaluation. These services will be provided at no cost to SAIC through a cooperative agreement between TI and UT Dallas.

Progress in MEMs Laboratory Set-up

A laboratory environment at UT Dallas is being outfitted to facilitate vacuum chamber testing of MEMs pressure transducers. This laboratory includes a vacuum chamber measuring 20" in diameter by 36" in height, with mechanical and cryo-pumps to achieve pressure ranges down to 10-7 Torr. The vacuum chamber includes a laser interferometer suitable for calibrating the current-voltage response of the MEMS-based pressure transducers as a function of membrane deflection.

This facility will be available for laser-interferometer based testing, verification, and validation of pressure transducer designs over the range of pressures necessary to accomplish contract objectives (i.e., simulating the neutral atmospheric winds in a realistic background environment over the range of pressures to be found at atmospheric heights from 50-300 km). These laboratory facilities are available at no cost to the contract, and therefore represent a value-added opportunity for instrument calibration and testing.

B. *Instrument implementation - Hardware*

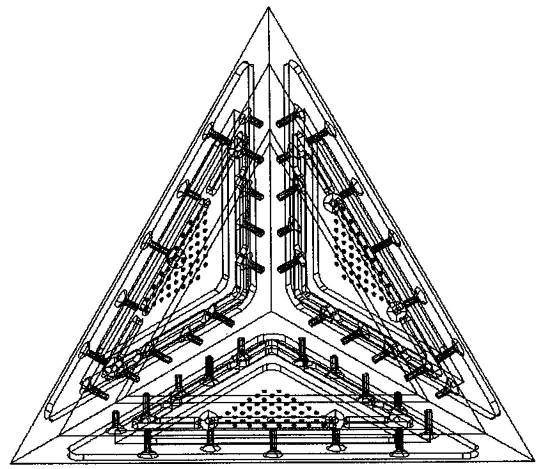
There are two major categories of hardware for the wind sensing instrument. One is the electronics including drivers and controls. The second is the actual instrument configuration, or system packaging.

Electronics

We have set up an electronics testing lab at SAIC for breadboarding of electronics. Current measurements will be made using multiple devices on each MEMS Detector Plate Array (DPA). This design is flexible in that a DPA may be an MCM or PCB holding individually packaged TDT's or the DPA may be an integrated array of TDT's on a single chip. Ambient exposure will determine the final configuration. Data from each device will be amplified, multiplexed and digitized by an embedded processor sub-system shown in Figure 3, which will monitor the output of each data channel and will provide closed-loop control of each data channel's gain offset to compensate for changes in background neutral density. The processor will use measurements

from multiple devices to reduce the signal to noise ratio and compute a neutral wind vector component for each MEMS DPA. Vector transformations can then be applied to convert the neutral wind vector to the standard 3-axis orthogonal coordinate system. Although electronics local to the MEMS components will be driven by the current measurement requirements, other system issues impact the electronics design as discussed below.

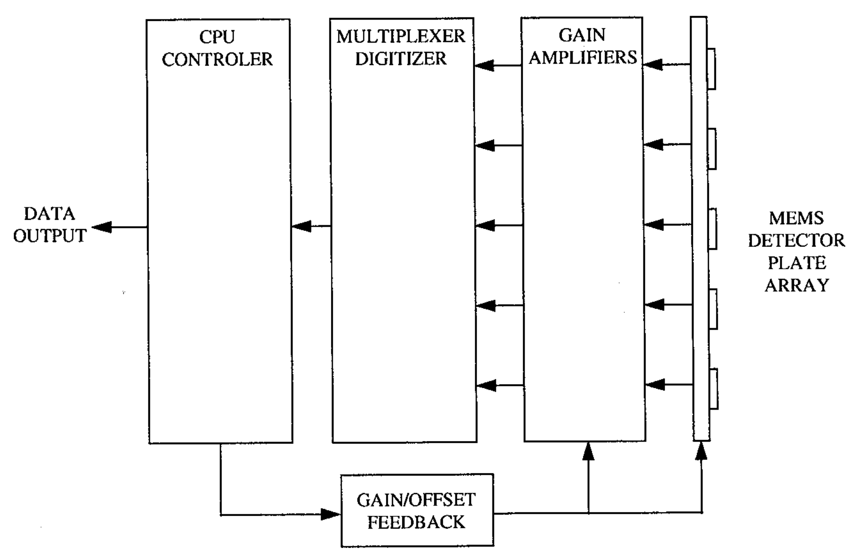
Figure 3



Instrument Packaging

The current mechanical design configuration consists of MEMS DPA's arranged as a three-sided pyramid. This design concept will allow for direct vector transformation discussed above. Design of the instrument housing and packaging is therefore intimately connected to the electronics and signed procession issues. Mechanical drawings as complete and a partial assembly showing position of the DPA's is shown in Figure 4. The three side plates will contain MEMS devices which measure the incident neutral winds. A fourth plate which forms the base of the instrument will measure background neutral pressures inside the pyramid to aide in data analysis. Each of the four MEMS detector plates will contain identical arrays of MEMS devices designed to accommodate a wide range of operating parameters.

Figure 4



C. Instrument implementation - Software

Software must be considered in the initial design phase as well. The major components for data acquisition and data procession, may also require augmentation for transducer control.

A flow chart lay out for the software to control the instrument elements is shown in Figure 5.

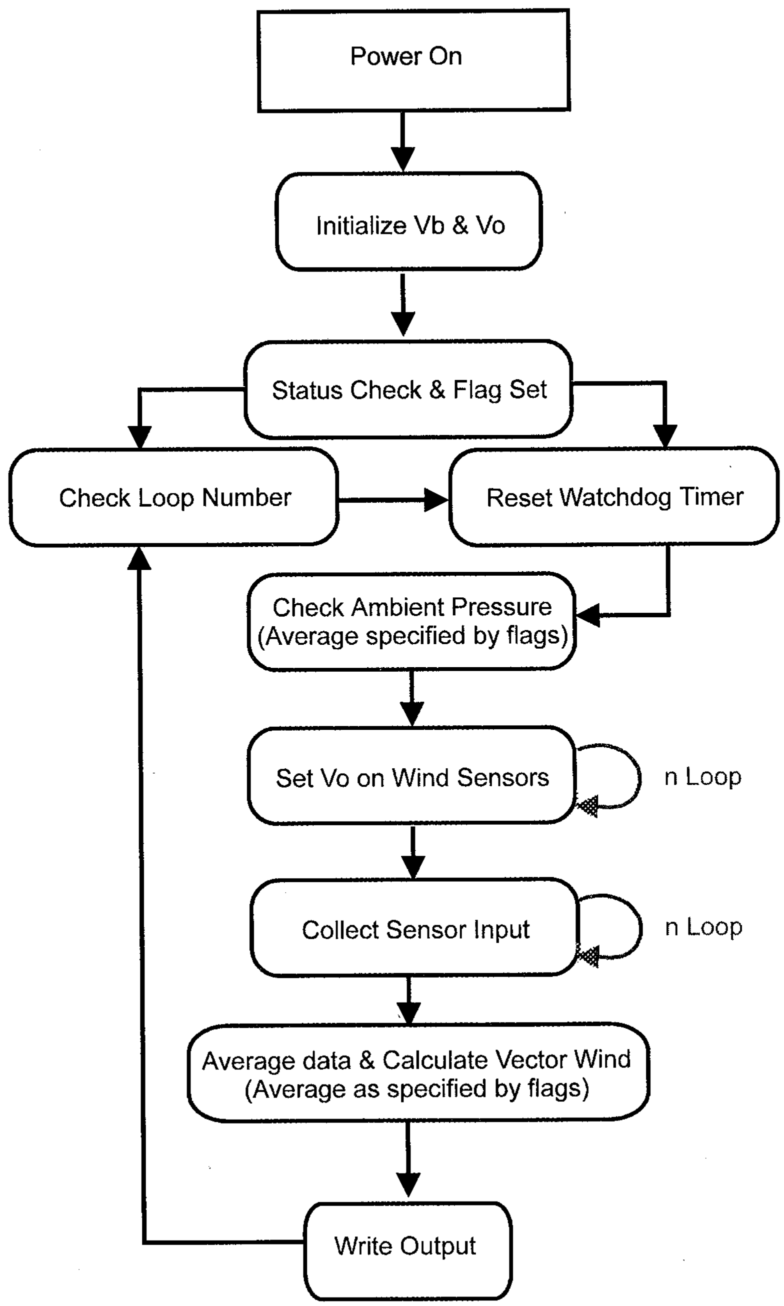


Figure 5

The flow chart illustrates the main blocks in the controller program that controls the electrometers and MEM-TDT sensors that lie at the heart of the wind meter. The controller is a TMS320 digital signal processor (DSP) made by Texas Instruments. To reduce execution time the controller program is written in assembly language. Once the power-on initialization of the processor occurs the program reads initialization values from a table in memory, then writes digital values for the TDT bias and offset voltages to a digital-to-analog converter (DAC). These voltages establish the initial conditions under which the devices will function. Each device will be independently controlled so that their individual calibration characteristics can be accounted for by the processor. Once each device is initialized the program sets internal flags indicating the status of each detector. On subsequent executions of the main program loop these flags will be individually interrogated to ensure that each sensor is operating correctly. If a single sensor fails it will be omitted from the averaging process that is used to determine the wind speed and direction. After the flags are set the watchdog timer is reset - its purpose is to re-initialize the program in case an interruption occurs in the instrument power. Next the ambient pressure from the neutral atmosphere is measured by averaging the membrane deflection of all the working TDT sensors. This ambient pressure measurement is used in specifying the offset voltage on the sensors prior to the vector wind measurement. After allowing sufficient time (a few microseconds) for the sensor offset currents to stabilize, the microcontroller polls each electrometer to read the current corresponding to the deflection of each sensor membrane. The wind is calculated by the controller through an averaging process over the differential measurements between opposing sensors. Once the output of the calculation is written to the output buffer the program control reaches a branch point - depending on the iteration number through the main program loop the measurement is either repeated or the status of each sensor is checked so that individual sensor malfunctions can be identified, and the averaging process modified accordingly.

Programming and debugging the TMS320 program is accomplished using a dedicated PC-based Texas Instruments development station. This development toolkit consists of a TI evaluation board containing an actual TMS320 chip, a communication cable for the PC interface, and a suite of software that allows the user to watch the on-chip processing as the program executes, set break points and watches, and simultaneously monitor all of the address registers, the accumulator status, and the auxiliary status registers.

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